

**STUDY OF AN UNMANNED LUNAR  
MISSION FOR VOLATILE GAS RECOVERY  
(PHASE 1 – FINAL REPORT)**

**WCSAR-TR-AR3-9309-1**

# ***Technical Report***



**Wisconsin Center for  
Space Automation and Robotics**



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# **Study of Unmanned Lunar Mission for Volatile Gas Recovery**

## **EXECUTIVE SUMMARY**

This report summarizes a one-year study of a proposed robotic mission to assay the volatiles which can be recovered by heating the lunar maria regolith. These gases include H<sub>2</sub>, He, N<sub>2</sub>, CO<sub>2</sub>, and CO. The H<sub>2</sub> could be reacted with the mineral ilmenite (FeTiO<sub>3</sub>) to form H<sub>2</sub>O which along with the gases N<sub>2</sub> and CO<sub>2</sub> would be useful for human life-support. The He is of interest because it contains a high abundance of the <sup>3</sup>He isotope which has been identified as a potential fuel for nuclear fusion power plants sited on the earth.

The study provides an initial mission plan and can be utilized for follow-on assay missions which would quantify the abundance, location, and recovery technology required to exploit these lunar resources. This information would be communicated to earth stations so that a mission to the moon to extract significant quantities of these volatiles could be initiated after the year 2000.

The study consisted of five tasks, namely: Task 1.0 Mission Requirement, Task 2.0 Science Instrumentation, Task 3.0 Rover Design, Task 4.0 Converge on Optimal System Design, and Task 5.0 Launch Vehicle.

### **Site Selection**

This mission for volatile gas assay would prefer a site with high volatiles content but also, with some diversity. The relationship between the retained solar wind implanted He and the TiO<sub>2</sub> content of the soil was utilized to select a landing site at 9°N and 20°E on the Mare Tranquillitatis which is reasonably level for up to 100 km to the southeast. The proposed sampling protocol would be to collect two samples, nearly adjacent. If their results agreed within the experimental deviation, the rover would proceed 0.5 km along the planned route and select two new samples.

### Assay of Regolith:

The assay of the regolith samples would be accomplished by the scientific equipment in the following sequence : 1) retrieve the sample of regolith from the lunar surface; 2) reduce the sample to ~ 1.0 gram of particles < 200  $\mu\text{m}$ ; 3) weigh the sample; 4) characterize the mineral content ( $\text{TiO}_2$ ); 5) heat the sample to  $1200^\circ$  in a vacuum oven; 6) collect the volatile products; 7) characterize the volatile products qualitatively and quantitatively; 8) transmit the data.

An important component of the instrument package is the mass spectrometer which will be utilized to characterize the mineral content of the soil, especially Ti, and the volatile gases. A Fourier Transformer Mass Spectrometer (FTMS) was identified to be particularly useful with high resolution for ions in the 1 to 72 AMU range. Although a miniaturized FTMS was not available at this time, it was assumed that one could be constructed similar to the mass spectrometer developed for the Mars - MESUR program, which has an earth mass of 12 kg and requires 25 watts of power. Such an instrument should be able to detect  $^3\text{He}$  in the evolved gases; however, quantitative measurements of the He isotopic ratio in the presence of other gases requires experimental verification.

Parametric studies indicated that a one gram sample of high-Ti maria regolith released sufficient gases to create a pressure of ~70 Pa (0.56 torr) in a one liter container at  $30^\circ\text{C}$ , which is a sufficient sample for the mass spectrometer. A one-gram sample of surface regolith would occupy a volume of 0.8 cm and could be contained in a ferritic steel crucible 0.8 cm OD x 1.57 cm high.

This sample and container would be placed in a coiled electrical heater inside of an evacuated one-liter container. The heater was well-insulated to prevent heat losses. Heat transfer calculations indicate that the sample would attain  $1200^\circ\text{C}$  in 6 minutes with a 50 W heater and 14 minutes with a 25 W heater. Before the sample is heated, a laser beam delivers 0.45 to 2.0 J per pulse at a wavelength of  $1\mu\text{m}$  to the surface of the

sample. This absorption of the laser energy vaporizes some of the minerals in the soil. These vaporized ions are quantitatively determined by the mass spectrometer.

A lunar rover platform with the sampler equipment attached has been conceptually designed. A scoop from this platform is lowered and filled with a surface layer of soil as the rover slowly moves forward. The scoop is rotated upwards and the sample passes through two vibrating screens and into the sample container. The sample and container are weighed on an automated scale which is calibrated before each sample. The sample container of ferritic steel is handled by magnetic chucks and placed in the heating chamber. The total mass on the platform is 17.9 kg. A sequential time program for one sample analysis indicates that from the start of the sample collection, through the analysis to transmitting the data requires 1100 s (18.3 min). With a 25 W heater 73 % of the time is used heating the sample.

#### **Mission Systems and Design:**

An iterative design procedure was utilized in which the mass, size and power requirements for the instrument package were imposed upon a rover design. The rover design was, then, input to the lander design which subsequently formed the requirements to the launch vehicle and upper stage design. From these iterations two solutions emerged: one based on the Delta launch vehicle and the other on the Atlas launch vehicle.

Several ground rules were assumed, namely: (1) only one lunar mission would be planned; consequently, Research and Development costs for new hardware should be avoided; (2) flight qualified hardware should be utilized whenever possible; and (3) maximize the science data as long as a medium class launch vehicle could be used.

Although few rover designs exist an algorithm was developed to trade rover mass, rover power and science instrument mass. This analysis indicated that an "average" rover subsystems which includes communication, thermal, manipulation, computation, control chassis and structure have a mass fraction of 0.72. Power



subsystem mass was calculated assuming General Purpose Heat Source, RTG's with a specific power of 5W/kg and a power management battery of 30 W-hr/kg.

Two existing rover designs were found to be compatible with this study, namely; (1) the 75 kg Small Marsokhod with a 100 km range for a Delta class mission; and (2) the JPL 290 kg Lunar Site Characterization Rover with range up to 1000 km for an Atlas class mission.

The Small Marsokhod (SMR) which was extensively displayed in the USA during 1992-93 was selected for this study. Its principal advantage is high probability in heterogeneous terrain; however, it has articulated motions with increased complexity which would probably not be needed on smooth areas of Mare Tranquillitatis, especially if it had telerobotic ability to avoid craters.

Various Artemis lander designs with lunar descent stages appropriate for medium class launch vehicles were evaluated for this study. A low earth parking orbit of 185 km x 185 km x 28.5° was assumed. Three lander options were examined: (1) a Bipropellant Lander, BL; (2) a Bipropellant Lander upper stage and a Solid Propellant Lower Stage (BL & SLS); and (3) a Bipropellant Lander upper stage and a Bipropellant Lower Stage (BL & BLS). An algorithm was developed showing Landed Payload Fracture as a Function of Dry Landed mass for the three architectures.

An estimated SMR mission cost was estimated based upon the USAF Unmanned Spacecraft Model, 5th Edition, with all costs normalized to \$1990. the estimated Space Segment costs were close to the goal of \$200 M. When costs were added for Launch Segment, Ground Segment and Operations and Maintenance the total Life Cycle Costs over the life of the mission were \$357 M.

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## **I. INTRODUCTION**

### **A. Purpose of Study**

The purpose of this study was to prepare a near-term mission plan which would lead to a systematic assay of the volatile gases retained in the lunar soil particles. This report summarizes a one-year study of such a proposed unmanned mission. This study provides an initial step in the mission plan and can be used as a basis for further programs, culminating in a mission to the moon to extract significant quantities of lunar volatiles after the year 2000. This latter mission would test key technologies for the recovery processes and establish the overall feasibility of further large scale volatile recovery missions.

Further unmanned exploration of the moon and other planets require that indigenous resources be utilized. Volatile gases derived from the lunar soil have been shown to be valuable resources for life-support and energy systems.

The following scenarios or a combination of them were suggested in the original proposal:

**Scenario 1:** Regolith would be sampled and concentrations of lunar volatiles measured at various locations on the moon for the purpose of determining sites for future resource operations. A robotic vehicle would collect and heat samples of lunar regolith to obtain the volatiles. These volatiles would be analyzed, and the results of the analysis would be communicated to earth.

**Scenario 2:** Regolith would be collected on a continuous basis and concentrations of the lunar volatiles would be determined at a localized area on the moon. A robotic vehicle would collect the regolith, extract the volatiles, and compress and store the volatiles in an appropriate container. The concentrations of the volatiles would be identified communicated to earth, and the container holding the volatiles would be returned to earth and analyzed.

**Scenario 3:** Regolith would be collected on a continuous basis and concentrations of the lunar volatiles would be determined at a localized area on the moon. A robotic vehicle would collect the regolith, extract the volatiles, separate out He-3, and compress and store the He-3 in an appropriate container. The container holding the volatiles would be returned to earth and analyzed.

Scenario 1 was developed in this report because of its basic importance to the whole program and a desire to keep the direct mission cost below 200 M\$ for the R D & T and first production unit for the science package, rover and lunar lander.

A program flow is given in Figure I.1. The first task ( Task 1.0 ) of this study

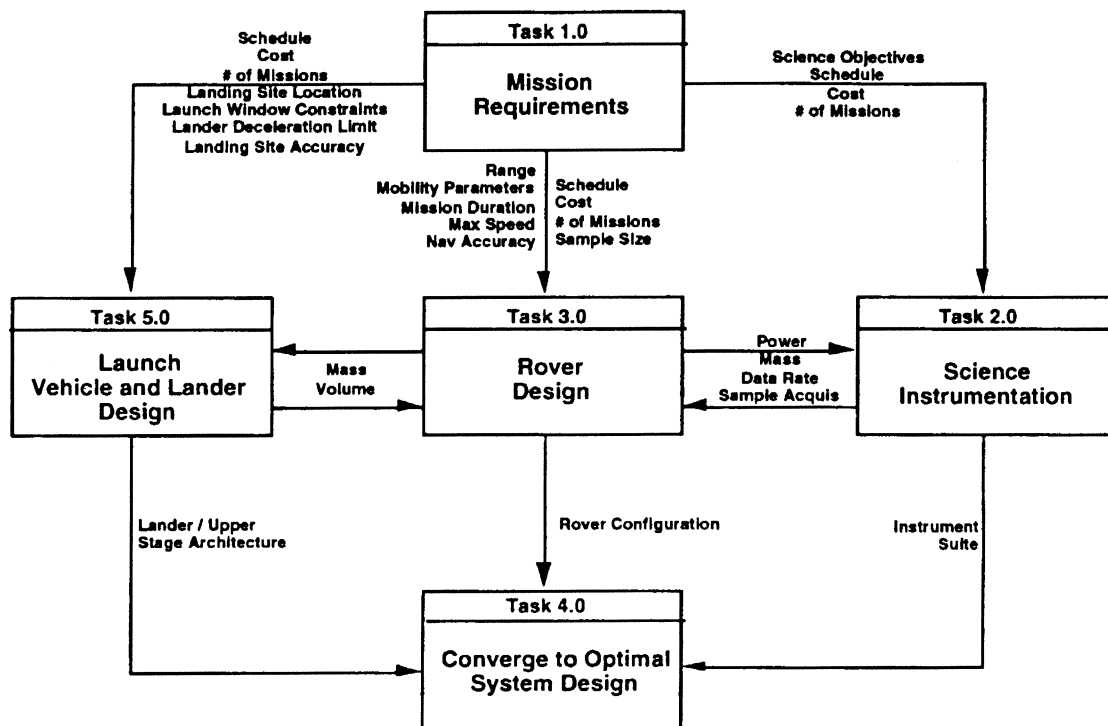


Figure I.1 Mission Study Overview.

was to establish the mission requirements and objectives of the mission. The second task (Task 2.0) involved the definition of various systems for recovery and analysis of the lunar volatiles. Task 3.0 involved definition of the various robotic vehicular systems required for the volatile recovery. Task 4.0 involved the integration of the robotic vehicle mission transportation requirements. Task 5.0 considered the launch vehicle and lander design options.

## **B. Background**

### **1. Occurrence of Volatiles on the Moon**

Further manned exploration of the moon and other planets and bodies within the solar system requires that indigenous resources be utilized in order to decrease the supply requirements from earth. Studies of the lunar soil samples, acquired by the Apollo and Lunar missions, indicate that upon heating in a vacuum these soils evolve the volatile gases  $H_2$ , He,  $N_2$ ,  $CO_2$ , CO and  $SO_2$ . The  $H_2$  would be valuable as a rocket fuel or it could be reacted with the mineral ilmenite to form water, while the  $N_2$ ,  $CO_2$  and the  $H_2O$  would be useful for the life-support of space-travelers. The element He is of interest because it contains a high abundance of the rare isotope  $^3He$ , which has been identified as a potentially valuable fuel material for the nuclear fusion/electrical generating power plants being developed for use on earth [1].

In order to assess the feasibility and economic potential in exploiting these lunar volatiles, we must be able to assess the total quantity of these volatiles and identify the most abundant sites. The delineation of the most abundant sites may require the analyses of a large number of soil samples because the sites visited by the Apollo astronauts were only a small fraction of the lunar surface. It is not known if the volatile gases in the soil vary widely over a distance of a few meters or several kilometers. Also, analyses of the samples in the pristine lunar environment is highly desirable because of the contamination of terrestrial air and water which occurred for some of the Apollo

samples. For these reasons, the mission plan embraced a science package capable of quantitative measurements of the gases. This analytical equipment would be mounted on an unmanned rover, equipped with a sample retriever, and have the ability to travel 10's of kilometers.

## **2. Relationship of Lunar Volatiles to Other Soil Constituents:**

The occurrence of most of these volatile gases in the lunar soil is related to the solar wind ions which travel outward from the sun. The composition of the solar wind ions is >90% H<sup>+</sup>, 4 -5% He<sup>+</sup> plus other light ions. The He has an unusually high <sup>3</sup>He/<sup>4</sup>He ratio of ~480 ppm (atomic) indicating that some of the <sup>3</sup>He escapes from the sun's interior without undergoing nuclear fusion. These solar wind ions travel at a velocity of ~450 km/s with a flux of  $\sim 6 \times 10^{10}$  ions/m<sup>2</sup>·s. Because the moon is not protected by a magnetosphere or an atmosphere, such as occurs on earth, these ions bombard the lunar surface and become embedded in the exposed rocks to depths of <1 μm. Several factors have been identified which can be used as guidelines to indicate the abundance of the solar wind ions in the exposed lunar surface.

## **3. Size Effects**

The lunar regolith is a surficial layer of fragmented rock, which overlies the lunar bedrock. The regolith has been produced by the impact of innumerable meteorites, both large and very small, that have bombarded the moon for the past 4.5 billion years. This bombardment pulverizes the rock into particles which range in size from millimeters to <20 μm. The particles of this regolith <1 mm dia. are known as "lunar soil". The impact of the meteorites often eject regolith from below the surface to the exposed surface. By such a continuous process, called "gardening", the regolith has been mixed to a depth of several meters. The highland regoliths, 10-15 m thick, cover

the bright mountainous areas of the moon, while the darker maria regoliths are 4-5 m thick.

The soil particles at the lunar surface are exposed to the solar wind ions whenever they face the sun. Because the ions penetrate only  $<1\ \mu\text{m}$  into the particles; these ions essentially form only a surface layer on a particle. Consequently, it has been observed that the smaller particles with a high surface to volume ratio have the highest concentration of solar wind ions per weight of particles [2].

#### **4. Chemical Effects of the Soil**

The composition of the lunar rocks include the silicate suite plus oxide and sulfide minerals. Analyses of Apollo 11 lunar solid samples indicated [3] that the He atoms were especially well retained in soil particles which bore fragments of the mineral ilmenite,  $\text{FeTiO}_3$ . As shown in Figure I.2, the relationship between He content and  $\text{TiO}_2$  in the regolith is approximately linear [4] between 2 and 8 wt %  $\text{TiO}_2$ . Above 8 wt %, the He content remains high; however, the scatter in the He content increases and has not been adequately explained for these Apollo 17 samples. The scatter may reflect the fact that the samples are mixtures of highland and maria regoliths in the Taurus-Littrow valley. Recently, experimental evidence has shown that poor He retention of silicate materials is due to the fact that continued solar wind bombardment of the surface forms amorphous coatings which release the trapped He. Conversely, the ilmenite particles are much less susceptible to such radiation damage and, consequently, provide better retention of the He. This information indicates that the surface of the moon which contains high concentrates of the element Ti in the mineral ilmenite should be an indication of high He content. This mineral occurs principally in certain maria but not in the highlands.

## **5. Soil Maturity**

Soil maturation [5] occurs when the regolith on the lunar surface is bombarded by micrometeorites which often cause melting of the soil particles followed by the solidification of glassy particles called "agglutinates". It has been shown that higher agglutinate fraction of the soil correlates with high exposure rates. Often associated with the phenomenon of agglutinate formation is a chemical reaction due to the fact that  $H^+$  ions have been implanted in the exposed soil; consequently, when the soil particles are melted an atmosphere of hydrogen is formed which reduces FeO in the soil to metallic  $Fe^0$ . The dark shading of the lunar maria has been attributed to the accumulation of these fine  $Fe^0$  particles. The amount of these fine metallic Fe particles in the soil can be determined by ferromagnetic resonances,  $I_S$ . Consequently, soils exhibiting high ratios of  $I_S/FeO$  can be used as an indicator of high maturity and long exposure to the solar wind.

## **6. Remote Sensing Information**

As previously mentioned, the He concentration in the maria regolith appears to be a monotonic function of the ilmenite content of the soils, Figure I.2. Such a correlation makes it possible, therefore, to estimate the  $^3He$  content of unexplored areas of the moon based upon the  $TiO_2$  content because  $TiO_2$  can be determined by remote sensing techniques.

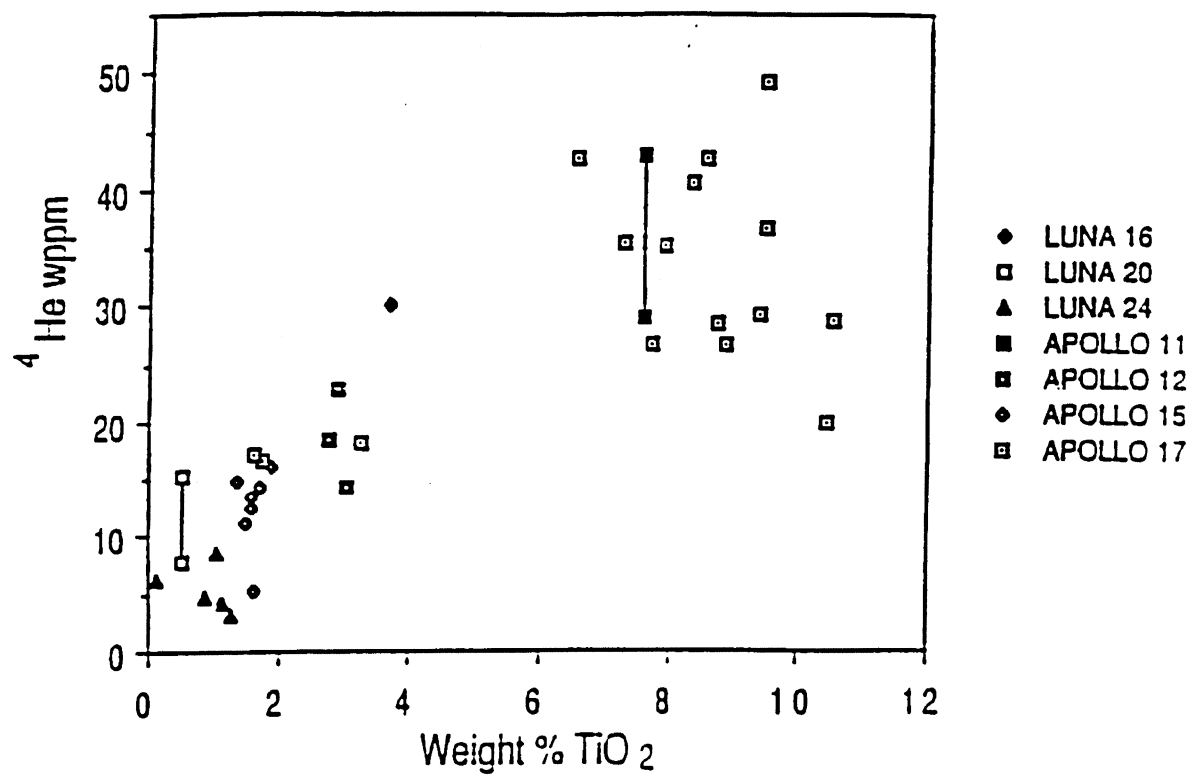


Figure I.2 Relationship between helium and titania in lunar regolith. The He-3 concentration is 0.0003 times the He-4 wppm [4].



Gamma ray spectroscopy of Ti, which made use of the radiation produced from cosmic ray bombardment of the lunar regolith, was recorded by the Apollo 15 and 16 orbiters as they encircled the moon near the equator [6]. Resolution of these data was poor and varied from 60 to 320 km; however, two maria of high-Ti regoliths were detected on the moon's near-side, Mare Tranquillitatis on the eastern side and the other in part of Oceanus Procellarium near the far-western side.

Optical spectroscopy techniques of reflected sunlight, as observed at earth-based observatories and by satellites, have provided high resolution of the TiO<sub>2</sub> contents of the moon's near-side. This technique makes use of ultraviolet negatives (0.40  $\mu\text{m}$ ) superimposed upon infrared negatives (0.56  $\mu\text{m}$ ) of the same area. These ratios are compared with similar color ratios determined from a reference area. The resulting ratios show consistency between 3 to 10 wt % TiO<sub>2</sub>. The initial spectral ratio map by T.V. Johnson [7] indicated an area of high TiO<sub>2</sub>, (<7% wt) along the eastern side of Mare Tranquillitatis. Later work by J.R. Johnson [8] produced enlarged maps of the west central region of Mare Tranquillitatis with a pixel-size resolution of 1.2 km. These maps indicated a region of greater than 7% TiO<sub>2</sub> and the terrain in this area may be more easily traversed than along the eastern side.

The 1990 Galileo spacecraft fly-by of the moon [9] using spectral reflectance spectroscopy indicated new regions of high TiO<sub>2</sub> within Oceanus Procellarium, especially near the Flamsteed region. The 1992 encounter of the same spacecraft with the moon [10] revealed another area of high TiO<sub>2</sub> content in the maria near the North Pole of the near-side.

### C. Site Selection and Sample Selection

The landing and sampling site for the mission should be well-characterized and be located on the near-side for continuous communications. In addition, it should have the following desirable characteristics: (a) reasonably high He content in the regolith but with some diversity. (b) terrain must be reasonably level for up to 50 km, with no large craters. Such sites have been identified by remote-sensing with TiO content in the range of 5 to 10 wt % in both the northeastern and northwestern sides of Mare Tranquillitatis. Photographs indicate, however, that the proposed sites in the northeast are rippled with small hills which may be difficult for the rover to climb; however, the northwestern sites have a less hostile terrain.

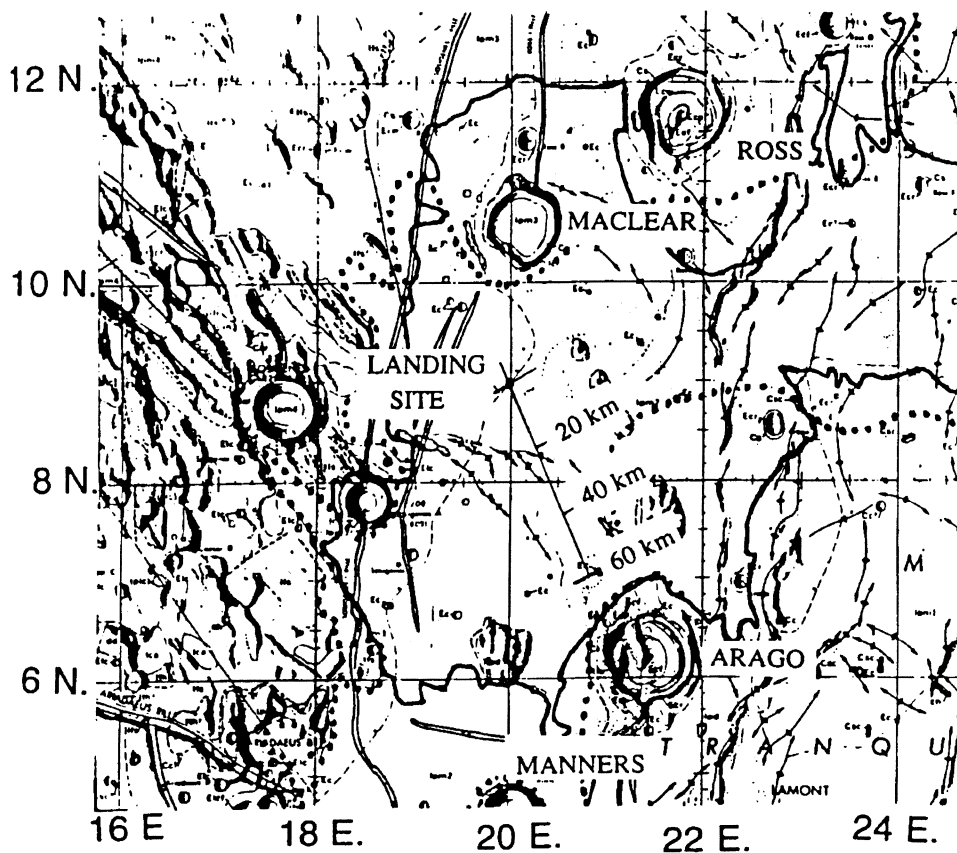


Figure I.3 Proposed lunar landing site.

For these reasons, therefore, the landing site selected [11] is at 9°N and 20°E. As shown in Figure I.3 this site would be located south of the craters Ross (26 km dia.) and Maclean (20 km dia), but north of the craters Arago (26 km dia) and Manners (15 km dia). Approximately 100 km of fairly unobstructed terrain exists south of Maclean.

The remote-sensing maps of J.R. Johnson were utilized in order to select a route for the rover which would sample a variety of regolith. This data suggested that from the landing site the rover could proceed in a southeasterly direction for ~60 km, as noted on Figure I.3, and sample regolith with contents of 6 to >10 wt % TiO<sub>2</sub>. Such regolith would have average He concentrations of 35-45 wppm (0.014 - 0.018 wppm <sup>3</sup>He).

The selection of a sampling strategy for the rover requires several considerations. Initially, as shown in Figure I.2, for Apollo 11 samples at 8 wt % TiO<sub>2</sub>, the He analyses varied by ±20% about the median of 35.5 wt ppm He. Insufficient information is available to determine if this is due to the inherent statistical variation between the two samples, or if this variation is due to some external effect such as the depth of the sample in the regolith or the way the samples were retrieved and, subsequently, handled in the laboratory before the volatiles were evolved. A large number of samples in a small target area of the lunar regolith would need to be analyzed in order to define the statistical magnitude of the variation.

On the other-hand, much wider sampling ranges extending up to 10's of km would reveal broader, more regional variations of importance to resource assessment. Such sampling would provide calibration for the remote-sensing orbital missions.

For the first Lunar Prospector mission the sampling protocol should probably be a compromise between the two strategies. For instance, two independently gathered samples adjacent to each other would be analyzed. If their He analyses were within, perhaps ±10%, the rover could proceed to a new site. The pixel sizes of the Johnson spectral photographs of Mare Tranquillitatis were 1.2 km and spectrographic reflection of data often showed changes between two adjacent areas. Consequently, the rover

could be moved up to 0.5 km between sampling sites to determine if the soil samples varied gradually or abruptly. If the rover transited the 60 km route previously described, a total of 120 sites would be surveyed and 240 samples would be analyzed.

#### **D. Description of Analytical Techniques Selected**

The primary focus of this lunar surface mission would be the quantitative analysis of volatiles derived from heating pristine lunar regolith samples which were never contaminated by the earth's atmospheric constituents. These gases would be contained in a vacuum chamber so that PVT measurements could be employed to determine the quantity of the gases. The chemical constituents of the gases would be determined by mass spectrometry. Several types of small mass spectrometers were surveyed for this application such as: time-of-flight, Fourier transform - ion cyclotron resonance and quadropole mass spectrometers. During this evaluation the common magnetic-deflection mass spectrometer was omitted because of the weight of the permanent magnet. A small quadropole mass spectrometer, similar to that design for the Mars MESUR mission [12] was selected, as described in Section II.

In order to further characterize each regolith sample, its Ti content would be determined. This determination would be accomplished when an intense, small laser beam would impinge upon the sample in the furnace prior to the heating of the sample. The absorption in the regolith of this laser energy would vaporize some of the sample as Ti ions and perhaps TiO ions. The identification and quantity of these ions would be determined by the same mass spectrometer used to analyze the evolved volatiles.

#### **E. Scope of Study**

##### **1. Introduction**

##### **Task 1.0 - Mission Requirements**

This study proposed a near-term unmanned mission plan to assay the volatile content of the lunar soil over a route of 10's of km on Mare Tranquillitatis. Requirements and equipment were evaluated or designed for the science package, the

sample retriever system and the rover. Several lunar lander and existing launch vehicles were considered. Several iterations were made with a costing-code to constrain the total mission cost.

The purpose of this study was to prepare a pre-conceptual design of an unmanned, lunar rover which would be landed by an early-return transportation vehicle on the lunar near-side with the capability to analyze the volatiles in the soil.

#### **Task 2.0 - Science Instrumentation**

The rover deploys a retriever apparatus which obtains a sample of the regolith and places it in a vacuum chamber for heating to liberate the volatile gases and measures the Ti content of the soil. A description of this instrumentation is given in Section II.

#### **Task 3.0 - Rover Design**

A rover design is presented in Section III which meets the requirements of the Science Instrumentation, and the vehicular mobility.

#### **Task 4.0 - Converge to an Optimal System Design**

Several types of lunar lander vehicles which would transport the rover to the lunar surface are discussed in Section III together with the power package.

#### **Task 5.0 - Launch Vehicle**

Several currently available U.S. launch vehicles are compared in Section III. Additional total life cycle cost of the mission, based on several different configurations, are delineated.

### **II.A. INSTRUMENTATION REQUIREMENTS**

#### **A. Description of Scientific Equipment**

The primary mission of this experiment is to attempt to correlate the He content in lunar regolith to the mineral composition. All indications from the samples brought from the moon point to the affinity of implanted He species to regolith samples which

are high in ilmenite ( $\text{FeTiO}_3$ ). This experiment will attempt to verify this conclusion by making a large number of measurements over an area in which, it is hoped, there will be variation in the mineral content of the regolith.

The functions which will be performed by the scientific equipment are the following:

- Pick up a sample of regolith from the lunar surface.
- Reduce the sample to  $\sim 1.0$  gm of particles  $< 200 \mu$ .
- Weigh the sample.
- Characterize the mineral content in particular, the quantity of  $\text{TiO}_2$
- Heat the sample to  $1200^\circ \text{C}$  in a vacuum oven.
- Collect the solar wind products.
- Characterize the solar wind products qualitatively and quantitatively.
- Transmit data.

## **1. Mass Spectrometry**

The most important component of the instrumentation package is the mass spectrometer. This instrument is the heart of the system and will be needed to characterize the mineral content of the samples as well as identify and quantify the released solar wind products. To be able to do this, the mass spectrometer must be able to identify particles from 1 to 56 AMU, where Ti is 47.9 AMU. More than 60% of lunar surface materials consists of oxygen, all tightly bound chemically to other elements. The next most abundant element is Si at 16 - 17%, followed by Al at 4.5 - 10%, Ca and Mg at 5% each, and Fe at 2.5 - 6%. Ti and Na make up the remaining 1% [13]. These are the major elements, however, there are other elements of much lower concentrations.

There are many different kinds of mass spectrometers. The one being considered here is the FTMS (Fourier Transform) mass spectrometer. The FTMS, also sometimes called FT-ICR (Fourier Transform Ion Cyclotron Resonance), was invented in 1973 and